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Research Paper

Probabilistic Seismic Hazard Analysis for Nepal

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A R T I C L E I N F O R M A T I O N

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A B S T R A C T

Nepal lies in the zone of Himalayan belt formed due to collision of two continental plates and have the high probability of earthquake occurrence. Many destructive earthquakes have been reported in past causing the massive destruction of lives and property. For reducing the risks caused by seismic events, proper study should be carried out beforehand, one of which is seismic hazard analysis. In this study, Probabilistic Seismic Hazard Analysis (PSHA) is carried out for Nepal and the hazard map is prepared in terms of Peak Horizontal Acceleration (PHA) for 500 years return period at bedrock level. The available earthquake catalogue for Nepal is processed for magnitude homogeneity and removal of aftershocks. The seismicity parameters are obtained using the method obtained for multiple catalogs with different level of completeness. The area source models are used for the analysis since the earthquake distribution is diffused and no particular information on faults is available. The attenuation relationship available for subduction zone earthquake is used for determining the PHA at a particular site. The software CRISIS2007 is used for computing and preparing hazard map for Nepal. The map is divided into number of sites using grids of 0.1º by 0.1º and PHA value at each grid is computed, finally, obtaining the hazard map for Nepal. The hazard map shows that the PHA value varies from 0.09*g* to 0.5*g* for Nepal, with the maximum values at Eastern and Western part of Nepal. This high level of seismicity in the regions shows that the proper plans should be implemented for reducing the risks caused by seismic events, like earthquake resistant design of structures.

1. Introduction

Nepal lies in the zone of Himalayan belt formed due to collision of two continental plates and have the high probability of earthquake occurrence. Many destructive earthquakes have been reported in past causing the massive destruction of lives and property. The recent devastating earthquake was Nepal-Gorkha earthquake of magnitude 7.8, occurred on 25 April 2015 causing death of over 8,000 people. As Nepal is prone to high seismicity, the structures should be built accordingly so that life safety is possible during major earthquakes. For the design of structures it is first necessary to determine all the possible parameters related to earthquake motion, so that the structures can be designed for the predicted value of earthquake motion.

Seismic hazard analysis is the quantitative estimation of ground shaking hazards at a particular site. At present

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day, this method is widely used for the determination of ground motion parameters. Seismic hazard may be analyzed deterministically, as when a particular earthquake scenario is assumed, or probabilistically, in which uncertainties in earthquake size, location and time of occurrence are explicitly considered. In the Probabilistic Seismic Hazard Analysis (PSHA), the site ground motions are defined for selected values of the probability of exceedance in a given time exposure period, or for selected values of annual frequency or return period for ground motion exceedance.

This study helps us to identify the worst scenario related to earthquake with reference to the past earthquakes for our country and by considering that worst condition we can develop some improved design methods for the structures.

2. Literature Review

PSHA in Nepal has been gaining recognition since the decade of nineties of the last century. In 1993, UNDP/UNCHS (Habitat) supported project was carried out to develop the seismic hazard map as a part of building code development project for Nepal by BECA World International (New Zealand) in association with SILT Consultants (P.) Ltd. (Nepal), TAEC Consult (P.) Ltd. (Nepal), Golder Associates Ltd. (Canada) and Urban Regional Research (USA). They conducted a PSHA for whole Nepal and obtained the contour of Peak Ground Acceleration (PGA) on medium soil for 500 years return period earthquake (BECA, 1993). Based on the result, the zoning of Nepal was done with zone factors ranging from 0.8 to 1.1 and the zoned map is used in building code of Nepal NBC 105:1994.

Later in 2002, an improved seismic hazard map for Nepal was developed using the software CRISIS99 prepared by Institute de Ingenieria, UNAM, Mexico, by Pandey et al for GoN. They have determined total 12 numbers of areal seismic source zones for whole Nepal and used the attenuation relation of Youngs et al (1997) for conducting the PSHA (Pandey et al, 2002). The final output consists of the seismic hazard map for peak horizontal acceleration (PHA) at bedrock that has 10% probability of being exceeded over 50 years. The PHA value varies from 100 to 450 gals for whole Nepal.

Parajuli et al (Parajuli et al., 2010) conducted the PSHA for Nepal in which separate earthquake densities are calculated based upon historical earthquakes and maximum magnitudes of faults using the Kernel estimation method which accounts the significance of both the number of earthquakes and size in 2010. Five attenuation laws developed for subduction zone are selected and used, giving equal weight to all to minimize the uncertainties. They presented a hazard map of Nepal for PGA at soft soil bedrock that has 10% probability of being exceeded over 50 years. They found that there is higher concentration around Kathmandu than other parts of the country illustrating the highest risk. They have also presented the probabilistic spectra for return periods of 100, 475 and 1000 years for Kathmandu city in this study. They suggest that there is an urgent need to revise the existing hazard estimate and code provisions.

Thapa and Wang conducted the PSHA for Nepal in 2013 by delineating 23 seismic sources zone and estimated the PGA at bedrock level with 63%, 10%, and 2% probability of exceedance in 50 years (Thapa and Wang, 2013). Morpho-structural zoning (MSZ) and pattern recognition technique (PRT) were used to determine the earthquake prone areas in Nepal Himalayas and surrounding region, which in-turn were used to delineate the potential seismic source zones. The ground motion attenuation relationship developed by CEA for western China was used in this study. The resulting ground motion maps shows the high hazard in the far-western and eastern sections, and low hazard in southern Nepal.

3. Methods Adopted

3.1 Earthquake Catalog and Processing

Earthquake magnitudes and epicenter list occurring in Nepal from 1255 to 2017 A.D is collected from various data sources like National Seismological Centre (NSC), Disaster Preparedness Network Nepal (DPNet Nepal) and United States Geological Survey (USGS). The earthquake catalog consist of earthquakes in intensity (I_o) and various magnitude scales like local magnitude (M_L), surface wave magnitude (M_s), body wave magnitude (M_b) and moment magnitude (M_w). All the intensity values and magnitude scales are converted to M_w scale for homogeneity. The various conversion relationships are discussed below.

Conversion from I_o to M_L (Gutenberg and Richter, 1956):

$$= 0.67 \quad + 1.0 \qquad [1]$$

Conversion from M_L to M_s (Wang et. al., 2010):

$$= 0.98 \quad + 0.03 \qquad [2]$$

Conversion from M_b to M_s (Liu et. al., 2007):

$$= 1.07 \quad - 0.63 \qquad [3]$$

Conversion from M_s to seismic moment, M_o (Ambraseys & Douglas, 2004):

$$= 16.03 + 1.5 \quad (\qquad > 5.94) \qquad [4]$$

$$= 19.38 + 0.93 \quad (\qquad \leq 5.94) \qquad [5]$$

Conversion of M_o to M_w (Hanks & Kanamori, 1994):

$$= 0.67 \qquad - 10.63 \qquad [6]$$

The earthquake catalog consists of mixture of aftershocks and main events. For the purpose of PSHA, only main events are required as aftershocks are non-Poissonian in nature. The dynamic window declustering method proposed by Gardner and Knopoff (Gardner & Knopoff, 1974) is used to remove the aftershocks from the earthquake catalog. The raw earthquake catalog for Nepal and surrounding region consists of total number of 2118 earthquake data from 1255 to 2017 A.D. which, after declustering, the number reduced to 965.

3.2 Seismic Source Zones

Seismic source delineation is generally premised on geoscience knowledge that relates earthquakes to geologic structure. For this study, the seismic source zones developed by Thapa and Wang (Thapa and Wang, 2013) are used for conducting the PSHA. Same source zone models were used by Md Moklesur Rahman and Ling Bai in their study (Rahman and Bai, 2018). Total 23 numbers of areal seismic zones are used for computing the hazard for Nepal as shown in **Fig. 1**.

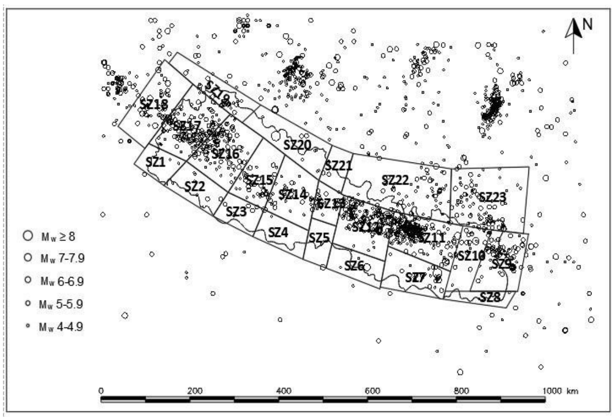

Fig. 1. Seismic Source Zones

3.3 Minimum and Maximum Magnitudes

For the PSHA purpose, the earthquake magnitude below some minimum value can be neglected because its significance on the structures is less. Here, the minimum value of earthquake magnitude is taken as 4, which is generally used in case of PSHA.

The assessment of maximum earthquake magnitudes for area sources is particularly difficult because the physical constraint most important to the assessment, the dimensions of fault rupture, is not known. As a result, the primary methods for assessing maximum earthquakes for area sources usually include a consideration of the historical seismicity record and analogies to other sources (SSHAC, 1997).

3.4 Seismicity Parameters

Gutenberg-Richter a- and b-value are the main parameters that are required for PSHA. The earthquake catalog consists of both historical and instrumental seismicity for a long duration of time. Usually historical seismicity consists of large earthquake magnitudes only and they are incomplete for small earthquakes. To determine the seismicity parameters using least square regression analysis, the catalog must be complete for all the magnitudes. Another method for estimating the seismic activity parameters is to reject the incomplete part of catalog and use any standard method for the data from the other complete part of the catalog (Kijko and Sellevoll, 1989). But, using this process neglects the large magnitude value which leads to large error in obtained values (Knopoff and Kagan, 1977; Dong et al, 1984).

For this purpose, the β-value and activity rate are obtained using the method proposed by Kijko and Smit (Kijko and Smit, 2012). This method is used for the incomplete catalogues. Incomplete catalogues are defined as a catalogue that can be divided into sub-catalogues each with different levels of completeness. For this study, the earthquake catalog can be divided into two parts; first part consists of data from 1800 to 1963 A.D. and second part consists of data from 1964 to 2017 A.D. (Thapa and Wang, 2013). The various seismicity parameters obtained for sources are shown in **Table 1**.

Table 1. Seismicity Parameters for Source Zones

Source	β	b	λ	a	M_{max}
SZ1	1.98	0.86	0.034	1.97	6.4
SZ2	1.98	0.86	0.041	2.05	6.4
SZ3	1.98	0.86	0.047	2.11	6.4
SZ4	1.98	0.86	0.014	1.57	6.4
SZ5	1.98	0.86	0.014	1.57	6.4
SZ6	1.98	0.86	0.027	1.87	7.0
SZ7	1.98	0.86	0.155	2.63	8.4
SZ8	1.98	0.86	0.014	1.57	6.4
SZ9	1.98	0.86	0.189	2.72	8.0
SZ10	1.98	0.86	0.284	2.89	8.4
SZ11	1.98	0.86	0.392	3.03	8.4
SZ12	1.98	0.86	0.304	2.92	8.0
SZ13	1.98	0.86	0.088	2.38	7.5
SZ14	1.98	0.86	0.263	2.86	8.4
SZ15	1.98	0.86	0.149	2.61	8.4
SZ16	1.98	0.86	0.419	3.06	8.4
SZ17	1.98	0.86	0.480	3.12	8.4
SZ18	1.98	0.86	0.270	2.87	8.0
SZ19	1.98	0.86	0.054	2.17	6.4

Source	β	b	λ	a	M_{max}
SZ20	1.98	0.86	0.108	2.47	6.4
SZ21	1.98	0.86	0.014	1.57	6.4
SZ22	1.98	0.86	0.345	2.98	6.4
SZ23	1.98	0.86	0.216	2.77	6.4

3.5 Attenuation Relationship

Ground motion parameter at any site is estimated using the attenuation relationship, which is a function of earthquake magnitude, distance and other geological and seismological parameters. Till date, no attenuation relationship has been developed for Nepal. For the PSHA purpose, the available attenuation relationship which best match the tectonic characteristics of Nepal are chosen. The attenuation relationship developed by Youngs et al. (1997) for subduction zone earthquake is suitable in case of our country as Nepal also lies in the subduction zone boundary. Youngs et al. (1997) provides attenuation relationship for both rock and soft soils, and the attenuation relationship is used for estimating both peak horizontal acceleration (PHA) and spectral acceleration (SA) for 5% damping value.

The majority of the seismic events in the Himalayan thrust belt are shallow, about 13-37 km focal depth (Shanker et al., 2011). Therefore, for our purpose, focal depth of 10 km is used which was also used by Thapa and Wang (2013).

3.6 Modeling and Analysis in Software

To conduct the PSHA, the above obtained geometries and parameters are modeled in software CRISIS2007 (Ordaz et al., 2007). CRISIS2007 is a windows based software with the capability of performing PSHA using a fully probabilistic approach allowing the calculation of results in terms of outputs with different characteristics (i.e., exceedance probability plots, set of stochastic events). All information that are required for conducting the hazard analysis are made input in the software.

Various steps involved in modeling and analysis are:

1. Input the map of Nepal in software.
2. Divide the area into smaller grids of 0.1° by 0.1°, in which each grid represents a single site where hazard is to be computed.
3. Define and draw the 23 numbers of area sources in the model.
4. Define the source seismicity by making input the G-R a and *b* value, threshold magnitude, maximum magnitude etc.
5. Define the spectral ordinates parameters to be determined. In this case, spectral ordinates are defined for time periods of 0 sec (i.e. PHA).
6. Define the attenuation relationship and assign it to the respective source zones.
7. Define the return periods for calculating the seismic hazard.
8. Run the analysis and view the outputs.

4. Results and Discussion

4.1 Seismic Hazard Map of Nepal

The output from the CRISIS2007 is the seismic hazard map for PHA. For our purpose the hazard map for return period of 500 years (i.e. 10% probability of exceedance in 50 years) is only considered since the design basis earthquake for Nepal is based on 500 years return period. The obtained hazard map is shown in **Fig. 2**.

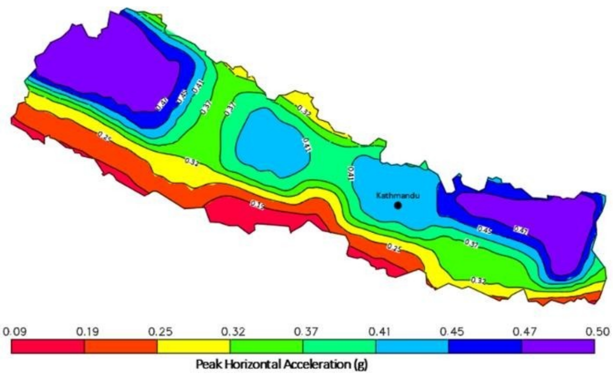

Fig. 2. Seismic Hazard Map of Nepal for PHA for Rock Sites (for 500 years Return Period)

From **Fig. 2**, it can be concluded that the PHA value varies from 0.09 *g* to 0.50 *g* for Nepal. It can be seen that the eastern and western part of country is more hazardous to earthquake.

4.2 Comparison of Obtained Value

The obtained value of PHA is compared with the values from different studies. For this, a comparison of the PHA value for Kathmandu is done. The comparison is shown in **Table 2**.

Table 2. Comparison of PHA value at Kathmandu

Researchers	PHA (g)
Pandey et al, 2002	0.25
Thapa and Wang, 2013	0.50
Rahman and Bai, 2018	0.53
This Study	0.43

As can be seen from the **Table 2**, the obtained value of PHA differs much from that of Pandey et al, 2002 only; this is because of the limited earthquake data available at that time and methods used for the analysis. At present, more number of data is available and new techniques are available for carrying out the hazard analysis, which gives the more refined results.

5. Conclusions

The seismic hazard map for Nepal in-terms of PHA is obtained performing the PSHA as shown in **Fig. 2**. The hazard map is prepared for return period of 500 years, which is considered as design basis earthquake for Nepal. The PHA value varies from 0.09 *g* to 0.50 *g* for Nepal. It can be seen that the eastern and western part of country is more hazardous to earthquake.

The hazard map can be used for land use mapping, mitigation and emergency response management. The ground acceleration values obtained can be used for earthquake resistant design of structures for a particular location. The hazard map should be updated timely as additional data and information becomes available from scientific analysis.

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Symbols and abbreviations

a, b	Gutenberg-Richter seismicity parameters
g	Acceleration due to gravity
I_o	Intensity
M_b	Body wave magnitude
M_L	Local magnitude
M_{max}	Maximum magnitude
M_o	Seismic moment
M_s	Surface wave magnitude
M_w	Moment magnitude
β	*b*ln (10)
λ	Activity rate